Intelligent sensor system for the structural health monitoring

J. Teng, H.J. Liu, W. Lu & Y.H. Zhu
Department of Urban and Civil Engineering, Harbin Institute of Technology Shenzhen Graduate School, Shenzhen 518055, China

ABSTRACT: The intelligential method and technique of the sensor system of the structural intelligent health monitoring system is studied with combining of the application of the hardware system of the Shenzhen Citizen Center proof grid structural health monitoring system. The high dependability and high stability of the intelligent structural health monitoring system is guaranteed by the intelligent properties of the front sensor systems by the techniques of system data automatic collection, system self-compensation and adaptive property, system disturbance immunity, the system data transforming and long-distance delivering.

1 INTRODUCTION

The sensors as the tools of gathering message are at the front of the structural health monitoring systems. It is very important for the properties, the dependability and the stability of the sensors to the entire system. It is demanded that the structural health monitoring system needs to long-term work with no interrupted for measuring the structural states, therefore, the sensors can work at rather abominable and changing environmental conditions like large range of temperature, moisture, rainfall, strong wind, thunder and lighting, freezing, under water and conflagration. It is very important for the sensor systems having stable and independent output with no parameters drift at any environmental conditions in long-term use that is the higher demand for the structural monitoring system with distinction to those in the laboratory.

Sensors are widely used in every territory like manufacture automation, military science, scientific test, calculation accounting and monitoring diagnosis, et al. It is worked hard in improving the properties of the sensors, however, the limitation of the properties of the traditional sensors cannot be overcame. The defects of the traditional sensors are:

(1) The size of the sensor is too large to affect the property of the measuring object.

(2) It is fall short of the properties of the time and frequency.

(3) The input-output property is nonlinear and drifts with time.

(4) The parameters drift with the influence of the environmental change.

(5) The overlapping sensitivities are involved in the system output and it is bad in choice and definition.

(6) It is low in the ratio of message to disturbance and easy to be influenced by disturbance. Those defects are the main reason of the properties instability, low dependability and low accuracy.

The sensor technique is the technique for the sensor design, manufactory and application synthetically, which is one of the three props to the information technology. The popularization of computers and speedily development of the message treatment technique makes large comparison of the lag development of sensor technique. The promotion to develop the sensor technique is formed with the developments of computer, information, intellectual technologies and the widely marketplace and the intense demand. The higher demand is proposed for the sensors in digitization, intelligentization and standardization.

The process monitoring and control is developed from centralized control in 1950s to 1960s, decentralized control (DCS) in 1970s and the open control system (FCS) based on the field bus in 1980s that is the inheritance, improvement and development to the DCS and the important development in the areas of automation and information engineering. The field bus is the both-way communication network connecting to the monitoring and control system with the intelligent sensors at the front of the intelligent instruments, that has the properties of

(1) The digitization of message transmitting, the standardized analog signal is substitute by the digit signal that enhances the abilities of the system in dependability and disturbance immunity. The field

sensors can easily connect to the ring-like bus by means of digital bus interfaces. The system design and wiring can be simplified enormously and the installation charge is thrift that is very important for the large and multi-drop test systems.

(2) Standardization, the open system is produced by unitary criterion to the bus and the hardware and software of different companies, the communication regulations, attended modes can be mutually compatible and join employed. The criterion terrace produces the technique development and convenience in application, installation and maintenance.

(3) Intelligentization, The rule of intellect and control function decentralized to the lower level of field instruments is adopted for the field bus and it is demanded that the intelligent instruments need to be installed at each joint and also the sensors need to be intelligent.

The intelligent sensors with standardized digital bus interface can self-administer and communicate with super-ordinate computers with the form of digital quantity though field buses. The intelligent sensors stand for the development direction of the sensor technique.

2 THE INTELLIGENT SENSORS AND THE INTELLIGENT SENSOR SYSTEMS

The intelligent sensor technique is the modern sensor technique of flourishing development that relates to microelectronics, computer technology, signal treatment technology, electric circuit and system, sensor technique, neural network technique and fuzzy theory et al. comprehensive technologies of more branches of learning. The intelligent sensors are the sensors combined with microprocessor supplying the functions of examination and message treatment and have the properties of perception, study, reasoning, communication and administration.

Sensor system is the combination of sensors, computers and communication techniques. The intelligent sensor system and the micro-sensor system are the main two directions of development for the sensor systems, the former is to endow with intellect to the sensor system and the latter is to achieve the micro-size for the sensors. It is important for the intelligent sensor system to obtain the intellect by intelligent combination of the sensors and microprocessor or microcomputer by means of the message transforming electric circuit. The intelligent sensors and systems have the properties of

(1) automatically collecting message;

(2) self zero bit removing, self-demarcation and adaptive property;

(3) automatic examine, self-select measuring range;

(4) automatic equalization;

(5) data store, memory and message treatment;

(6) two-way communication, standardized digital and symbol output;

(7) judgment, decision and procession. The distinguishes of the intelligent sensors contrast to the traditional ones are

(1) High accuracy. It has multiple items for the intelligent sensors to guarantee its high accuracy by means of self zero bit removing, self-demarcation, system error calibrate, statistics treatment in removing the accident errors.

(2) High dependability and high stability. The intelligent sensors can automatically compensate the system properties drifts under the changes of the work condition and environment, especially the zero bit and sensitivity drifts under the change of temperature, automatically change the measuring range when the target parameters change, automatically conduct system self-test, analysis and decide the rightful of the collect message and give an alarm when in particular situation.

(3) High signal-to-noise ratio and high definition. The disturbance noise are removed and the useful message is collected with application of the functions of store, memory and message treatment by means of digital filtering and correlation analysis. The techniques of message amalgam and neural network are used for removing the effect of overlapping sensitivities for the multi-parameters and the definition for the message of special parameter is enhanced.

(4) High adaptive. The optimal low power loss and optimal message transform velocity are applied for the system with the system self-strategic decision of the power supply and the velocity transforming message to the super-ordinate computers according the real work state because of the intelligent sensors' functions of judgment, analysis and treatment.

(5) Low cost-to-performance ratio. The above functions are achieved with powerful software function and cheep integrated circuit and chip with combination to the microprocessor and microcomputer, however, the functions of traditional sensors have to be improved by selecting advanced sensors, painstaking design and debug.

3 THE ACHIEVE METHOD OF INTELLIGENT SENSORS

There are 3 kinds of method to achieve the intelligent sensor systems, the one is the non-integrated achieve method, the second is the integrated achieve method and the third is composed of the two achieve methods.

3.1 *The Non-integrated Achieve Method*

The non-integrated intelligent sensor system is composed of the traditional sensors, message transform-

ing electric circuits and microprocessors with digital bus interface. Its structure is shown in figure 1.

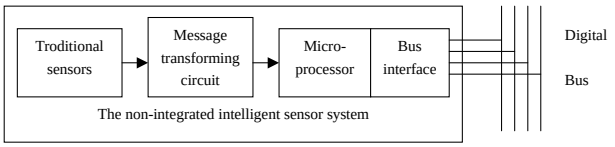

Figure 1 Frame of non-integrated intelligent sensor system

In the non-integrated intelligent sensor systems, the output message measuring by the traditional sensors is amplified and transformed into the digital quantity by the message transforming electric circuits and send to the microprocessor to connect to the field bus though the bus interface, that is the prompt manner to achieve the intelligent sensor system. The intelligent sensor systems are achieved by attaching the microprocessor with digital bus interface based on the original non-integrated transmitter and the intelligent software is used for communication,control, adaptive, self-compensation and self-diagnosis.

3.2 *The Integrated Achieve Method*

The micro machining and the large-scale integrated electric circuit are used in the intelligent sensors concentrated on the chip with the silicon sensors, message transforming electric circuits and microprocessors. The intelligent sensors are micron order with the micron order micro machining technology and large-scale integrated electric circuits based on the silicon material and it has the properties of

(1) Minimized, that the sensors have good compatibility to the structures and have no effect to the material properties of the structures and the work state of the sensors.

(2) Structural integration, it can achieve the entire system structural integration with the technology of micro machining and integrated technique.

(3) High accuracy. The repeatability performance will greatly improve and the time drift and parameter drift will greatly reduce when the sensors are structural integration in contracting to the non-integrated sensors. The parasitic reference effect can also be greatly reduced when structural integration without the fuse length problem for the follow-up transforming electric circuits.

(4) Multi-purpose. The sensors of different functions can applied into one silicon ship for the micron order sensor structure and not only the sensor functions is increased, but the stability and accuracy are lifted with the removing of the overlapping sensitivities by means of the collection message amalgam technique.

(5) Array Style. The thousands pressure transducers array into the only one square centimeter silicon chip with micron technology. The dependability, stability and definition are greatly lifted by removing the overlapping sensitivities and timing errors with the decoupling calculation, pattern recognition and neural network technologies when sensors ranged in array. The multi-dimensions sensor is achieved by image processing software when the sensors ranged in array.

(6) Whole digitization. For some kinds of sensors, the digital quantities is the direct output and directly interface to the microprocessor without A/D transforming.

(7) Easy to use and convenient in operation. It is easy to wire as it is no external joint elements. It can achieve entire self-check and need not long-term repeated multi-segments regulate and check.

4 THE INTELLGENT TECHNIQUES OF THE INTELLIGENT SENSOR SYSTEMS

The achievement of the intelligent functions of the sensors is the necessity tendency for the sensors overcoming themselves defects and obtaining the high accuracy, stability, dependability and definition. The intelligent functions are endowed with the powerful software by use the least hardware condition.

4.1 *Self zero bit check and self-calibrate technique*

The system input and output relation for the sensor system can be illustrated as

$$y = a_0 + a_1 x \tag{1}$$

in which, a0 is the zero pozation, a1 is the sensitivity or the transfer gain of the sensor system, they are constant when in ideal condition of the sensor system, however, they changed for different factors

$$y = (a_0 + \Delta a_0) + (a_1 + \Delta a_1)x \tag{2}$$

in which, Δa_0 is the zero bit move by which zero bit error occurs and Δa_1 is the sensitivity move by which sensitivity error occurs. In the traditional sensor techniques, it is to proposed the aborative design and manufacture, and the high quality material and elements are needed.

The intelligent software derivates the sensor system real timely self-check the zero bit and automatic calibration and the system errors and changeable disturbance errors aroused by the disturbance of temperature and voltage waving are removed and obtain the high quality measuring quantity with sensor elements of relative lower cost. The three steps measurement method is an efficient method for the system to remove the zero bit and sensitivity errors. The three steps are measuring the zero bit, demarcation and target measuring that conducts at one time inter-

val. If the standardized signal is provided by the criterion voltage, the standardized resistance or the standardized capacitance and the system accuracy is guaranteed by the standardized reference signal, The three steps measurement method is mainly used for the system follow-up segments total check and demarcation. If the standardized reference signal is supplied by the same property criterion with the measuring target quantity, the three steps measuring method is used for the system involving the sensor systems total check and demarcation.

The three steps measuring method has the advantage for the system check and demarcation when the sensors are combined with the microcomputers. The collecting velocity of the microcomputer is much faster than that with artificial operation, therefore the demand for the follow-up instruments can be further reduced. The time interval for the steps is ms time stage and the system unsteady error can be further reduced.

The three steps measure method is the effective method to remove the move error for both zero bit and sensitivity. The three steps are

a. Zero bit measure, that is the system output when system zero input

$$U_{01} = E_0 A \tag{3}$$

b. Demarcate, that is the system output when system standard input

$$U_{02} = (U_R + E_0)A \tag{4}$$

c. Measure, that is the system output when system target input

$$U_{03} = (U_X + E_0)A \tag{5}$$

When

$$V = \frac{U_{03} - U_{01}}{U_{02} - U_{01}} = \frac{U_X}{U_R} \tag{6}$$

it can obtained

$$U_X = V \bullet U_R = \frac{U_{03} - U_{01}}{U_{02} - U_{01}} U_R \tag{7}$$

The advantages of the three steps measure method are (1) there is no error when the gain is no change within the three steps time interval, (2) the input errors can be removed when the errors are constant within the three steps time interval and (3) the high quality standard input is needed to ensure the measurement precision. When in the intelligent sensor system, the three steps are process with computer in very shot time (within ms) interval, and the sensor elements quality demands can be reduced as to get the high quality sensor system.

4.2 *non-linear property self-calibrate technique*

To achieve the ideal linear relationship for the input-output property, it is difficult for the traditional sensors in the design of the sensors and the electric circuit segments, however, it is easy for the intelligent sensor systems with no mind of the serious nonlinear property of the input-output from the sensor and A/D transforming circuit. The scale switching is automatically conducted with revolting nonlinear property and the measuring input quantity is send as the output which is the ideal linear property of the system input-output. The repeatability is the only condition for the front sensors and the transforming electric circuit to achieve the linear property self-calibrate segment.

Function Chain Neural Network method is an effective method to propose the non-linear adaptive for the sensor systems which is to determine the constants of the revolting nonlinear property multinomial

$$x_i(u_i) = c_0 + c_1 u_i + c_2 u_i^2 + ... + c_n u_i^n \qquad (8)$$

The demarcate measurement sequences obtained in laboratory are (1) System input: x_i : x_1, x_2, x_3, …, x_N , (2) System output: u_i : u1, u_1, u_2, u_3, …, u_N , where i=1, 2, 3, … , N , N is the demarcate measurement number. In figure 2, the network connection gains of the Function Chain Neural Network are W_j (j=1, 2, 3), the number of which is the degree of the revolting nonlinear property multinomial.

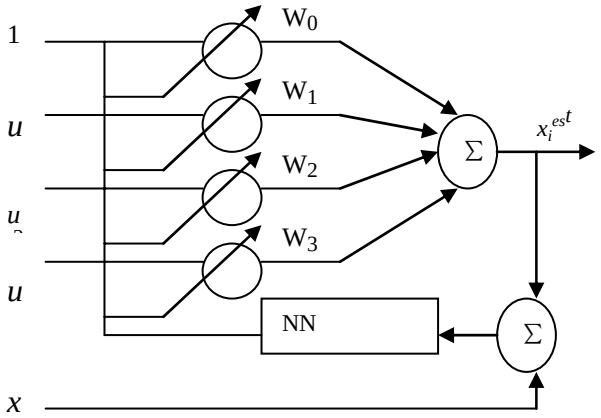

Figure 2 Function Chain Neural Network

When the Function Chain Neural Network input is (1, u_i, u_i^2, u_i^3), the output of the Function Chain Neural Network are

$$x_i^{est}(k) = \sum_{j=0}^{3} u_i^j W_j(k) \tag{9}$$

in which x_i^{est} evaluation of output compared with the demarcate measurement x_i and W_j are adjusted to ensure errors to be minimum. The evaluation error is

$$e(k) = x_i - x_i^{est}(k) \tag{10}$$

Connection gains is adjusted as

$$W_j(k+1) = W_j(k) + \eta_i e_i(k) u_i^j \qquad (11)$$

When the adjusted gains come to be unchanged, the constants of the revolting nonlinear property multinomial can be obtained as

$$a_i = W_i \qquad (i = 0,\ 1,\ 2,\ 3) \qquad (12)$$

When the Function Chain Neural Network are connected with the sensor system, it is become the intelligent sensor system with the function of nonlinear property self-calibration.

4.3 *The noise repressing technique*

The useful message presenting the property of the measuring target is automatically collect from in the noisy message. If the message frequency is not coinciding with the frequency of the noise, it can pass from the wave filter and noise frequencies outside of the message are stopped from the wave filter. The kinds of wave filter are divided into simulated wave filter of the time-continuous system realized with hardware and the digital wave filter of the discrete-time system realized with software. The digital wave filter has better stability and repeatability and easy to regulate. It can work in the frequency band that the simulated wave filter cannot achieve, though worse in real time, it is widely used. The digital wave filter is the main method in the intelligent sensor systems. If the frequency of the target message is overlapping to the frequency of noises or the amplitude values of the noises are larger than that of the message, the correlation technique is used to collect the useful message from in the noises.

4.4 *The Self-compensation Technique*

The software method is used in the monitoring compensation technique to directly measure the disturbance in the intelligent sensor systems. The revolting nonlinear property of the measuring is measured from the knowing input-output property at the temperature T and the temperature error is not added to the message quantity theoretically. The input-output property at the arbitrary temperature with incorrect demarcation condition is obtained with the curve fitting method.

If the message frequency is too high that the work frequency band of the sensors cannot meet the demand of allowable, the system frequency band needs to be extended and the dynamic property of the system needs to be improved. The powerful software of the intelligent sensor system can meet the needs and the frequency compensation can be achieved with the methods of digital wave filter and frequency adaptive.

4.5 *The Message Amalgam Technique of Multi-sensors*

The message amalgam technique is to lift the accuracy of each measuring quantity by measuring of multiple quantities and using the message treatment technique. The intelligent degree of the sensor system is improved with applications of the fuzzy theory and the Neural network theory and the system overcome the problems of unstable and low dependability because of the overlapping sensitivities and time drifting.

4.6 *The intelligent sensor self-check technique*

The intelligent sensor system can automatically check the system hardware faults and improve its dependability. The self-check is conducted at the situations of turned on, cyclic and button control. The different self-checks program is pitched for the system into the microprocessor with powerful logical decision and operation capability.

4.7 *The Intelligent sensor system self-diagnosis technique*

There are graceful degradation and arbitrary degradation involving to the sensor system that produce the system property worse and system breading down. The hardware redundancy method is to backup the sensor instruments of easy failure and management with vote switch. The functional/Analytical redundancy method utilizes the redundant relationship of each sensor in the system to the system diagnoses. The neural network is used for the sensor system diagnose and message recovering by the complex mapping from input model to the output model. The neural network method has the properties of powerful of nonlinear fitting, capability of fault-tolerance and fast in operation.

CONCLUSIONS

The properties of the sensors which is at the front of the structural health monitory affect the property and work state of the entire system and the intelligent degree of the sensor systems presents the intelligent properties of the entire monitoring system. The intelligent combination of the sensors and microprocessor is important to the intelligent health monitoring system and cause the system possessing the properties of study, reasoning, perception, communication and administration. The features of the system intelligent properties are the automatic removing of the system errors, self-compensation to the external disturbance, automatically removing the overlapping sensitivities and nonlinear errors, the high quality target message obtaining from in the noisy message and the system self-checking property. The intelligent properties are the development direction for the

structural health monitoring system in possessing of high stability, high dependability and high accuracy.

ACKNOWLEDGMENTS

The writers are grateful for the financial support of The National Natural Science Foundation of China, Grant NNSF-50278057.

REFERENCES

Johan H, Huijsing: Integrated Smart Sensors, Sensors and Actuators, 1992, 30, 167~174

Zhang Jinwu: The necessity, tendency and proposal of the sensor technique development, Journal of the apparatus and instruments 1997，18（5），132~135

Xia Changdi and Li Zhi: The Sensor Diagnosis Method Study with neural Network Technique, Journal of the Xinan Communication University，1995，30（2），151~157

Jiang Hongming: The System Examination and Recovering with the Message Amalgam for the Multi-definition Sensors, Journal of the Sensor Technique，1995（2），15~19

Shengcai Zhang: The new sensors of digital output, proceedings of the 2ed national conference on sensitive elements and sensors, 1991,208~210

Anserment S, et al: Cooperative Development of A Piezoresistive Pressure Sensor with Integrated Signal Conditioning for Automotive and Industrial Applications, Sensors and Actuators, 1990, A21-A23, 73~78

Sinnasamy R, Naidu, et al: Use of Neural Networks for Sensor Failue Detection in a Control System, IEEE Control System Magazune, 1990, (3), 49~55

Zhao Xinmin, Zhang Chen and Niu Yongsheng: The Failure-Sensor Signal Recovery with Autoassociative Neural Networks, Proceedings of the first International Symposium on Test and Measurement, 1995

Meijer G.C.M.: Concept and Focus Point for Intelligent Sensor systems, Sensors and Actuators (A), 1994, 41(15),183~191